the ATLAS Experiment

Exclusive heavy flavor production in ATLAS

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On behalf of the ATLAS Collaboration

DIS 2011

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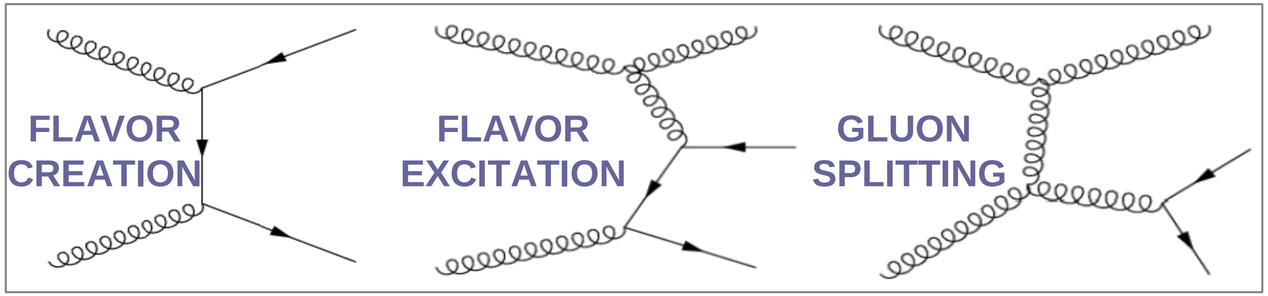
Overview

- Heavy Flavor in ATLAS
- ATLAS detector and 2010 data sample
- Full reconstructed HF final states
  - Di-muon in final state
    - J/Ψ
    - Open beauty
  - Hadronic decay
    - Open charm
- Conclusions

Heavy Flavor in ATLAS

$$pp \xrightarrow{pQCD}$$



$$Q \xrightarrow{NP\ \ fragmentation}$$

$$\frac{\sigma_{b\bar{b}(c\bar{c})}}{\sigma_{pp}} \approx \frac{0.24(4.4)\ mb}{60\ mb} \approx 0.4(7)\%$$

Huge σ but BGK too

$$H_Q \xrightarrow{EW\ decay} Exlusive\ Final\ state$$

EARLY DATA:

- Detector calibration candles: efficiency, resolution, scale, alignment, B and material mapping.
- Understanding heavy flavor hadro-production and polarization at the highest energy and smallest x regimes
- Understand background to other rare and/or interesting processes

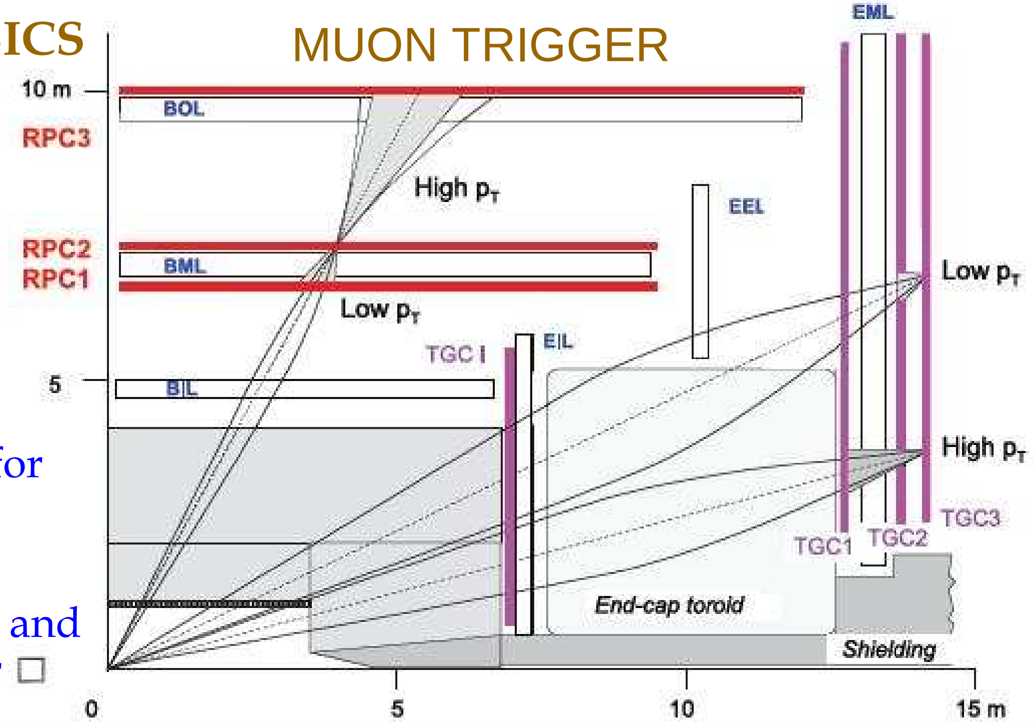
INTEGRATED LUMINOSITY > 1 fb^{-1}:

- B and D rare decays and CP-violation

μ tracking, Id and triggering

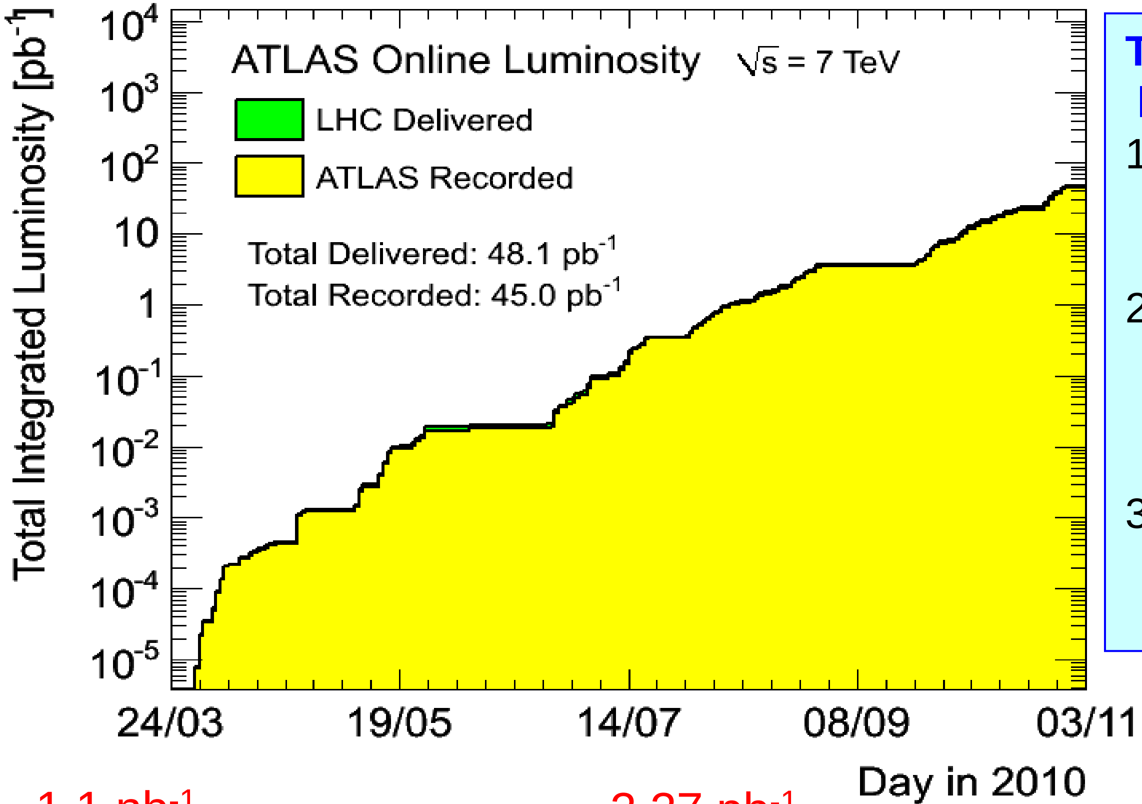
KEY SUB-SYSTEMS for B PHYSICS

- **Inner detector inside 2 T solenoid**
  - Tracking, vertexing and b-tagging
    - **$\sigma(1/P_T)$~1.5% at low P_T**
    - **$\sigma(d0)$~10um at high P_T**
- **Standalone muon spectrometer built around 4-5 Tm air core toroids**
  - Monitored Drift Tube ($|\eta|<2.0$) and Cathode Strip Chamber ($2<|\eta|<2.7$) for precision tracking
    - **$\sigma(1/P_T)$~10% at 1 TeV**
  - Resistive Plate Chamber ($0<|\eta|<1.01$) and Thin Gap Chamber ($1.01<|\eta|<2.5$) for □
    - **level 1 trigger (σ_τ~1ns) and 2-nd coordinate**
    - **Fast geometrical coincidence (roads)**
- **High Level Muon Trigger (HLT) with software algorithms**
  - **Single muon and di-muon triggers**



Data sample 2010

Peak Luminosity Record=$2.1 \times 10^{32} cm^{-2}s^{-1}$



Trigger changed with increasing luminosity:

1. **No HLT active.** Single and di-muon L1 triggers without minimum P_T threshold.
2. **HLT active.** A variety of single and di-muon HLT triggers with P_T thresholds ranging from 4 to 10 GeV.
3. **Higher luminosity.** Single muon triggers with low P_T thresholds prescaled.

Integrated Luminosity

1.1 nb^{-1} — D $d\sigma/d\eta$ and $d\sigma/dP_T$

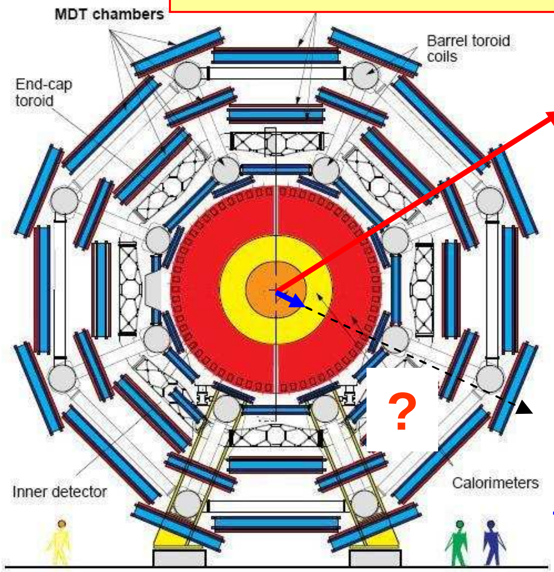
2.27 pb^{-1} — J/Ψ $d\sigma/(d\eta dP_T)$

3.4 pb^{-1} — $B^{+/-} \to J/\Psi K^{+/-}$

40 pb^{-1} — $B_{s(d)} \to J/\Psi \phi(K^*)$

Efficiency from Tag&Probe

Unbiased Efficiency maps from T&P:
- Reco vs Inner detector (next slide)
- L1 vs Reco
- High Level trigger vs L1&Reco
- Inner detector efficiency almost 1

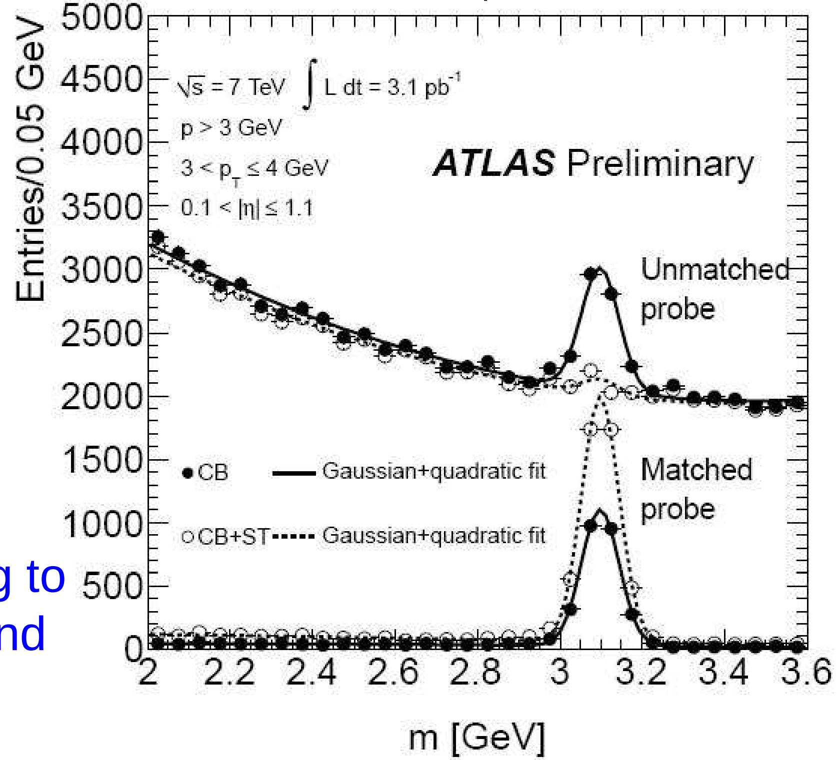


Tag = Combined muon matched with muon trigger to remove trigger bias

Probe = ID track combined with the Tag to get a J/Ψ mass (MS and trigger not used)

$0.1<|\eta|<1.1$

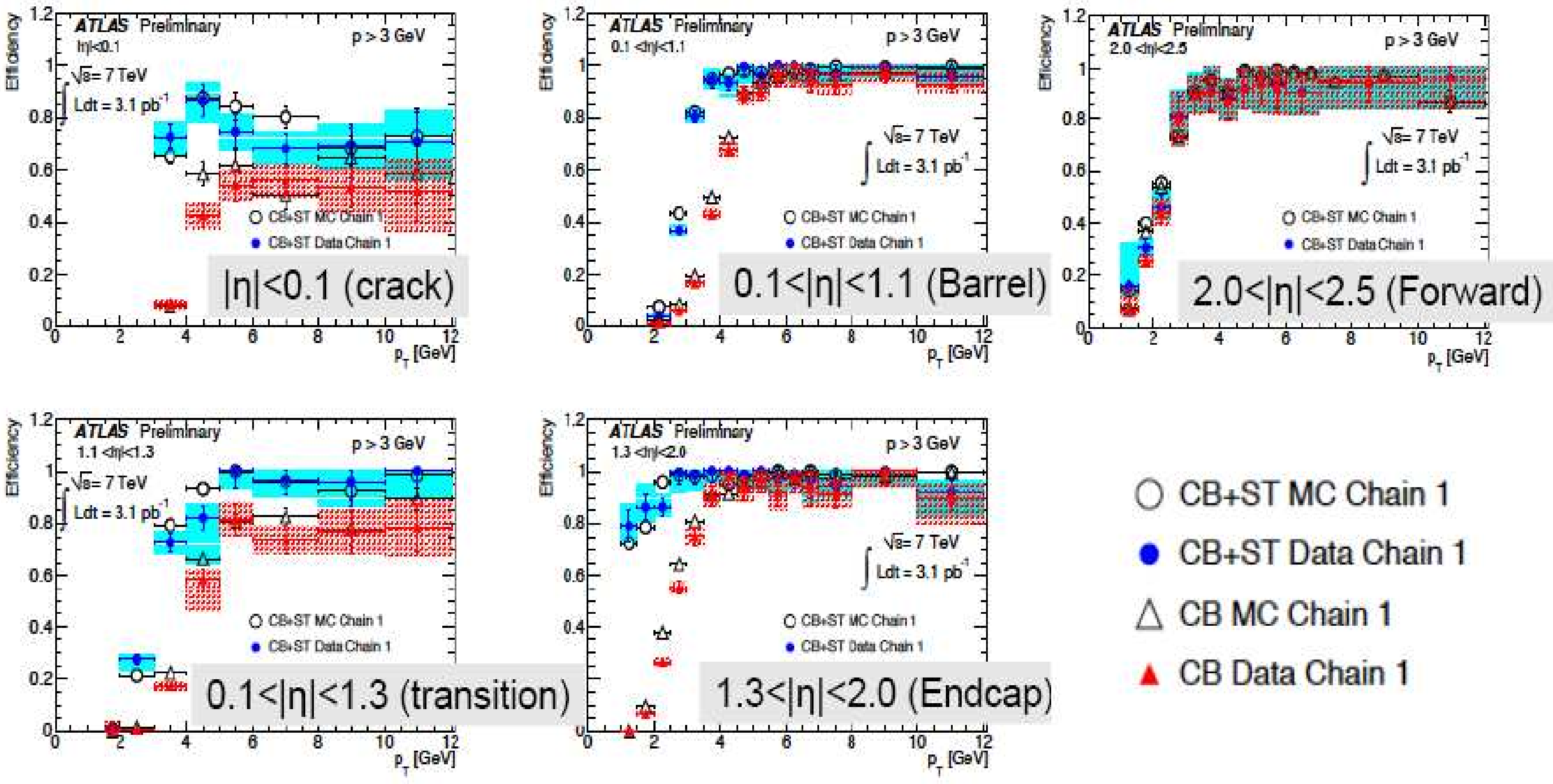
3 GeV $<P_T<$4 GeV



Efficiency=
Matched Probe Signal/
All Probe Signal

Muon reconstruction:
- Combined (CB): ID track combined with MS track
- Segment Tag (ST): ID track matched with MS segments

Muon Reconstruction Efficiency



J/Ψ double differential xsec

$$\frac{d^2\sigma_{J/\Psi}}{dP_T dy} B(J/\Psi \to \mu^+\mu^-) = \frac{N^w_{J/\Psi}}{\Delta P_T \Delta y}$$

Signal yield corrected event-by-event with weight w to get true yield

$$N^w_{J/\Psi} = N_{J/\Psi} w \quad w^{-1} = A\, M\, [1-(1-\varepsilon^+_{trig})(1-\varepsilon^-_{trig})]\, \varepsilon^+_{reco}\varepsilon^-_{reco}$$

- $A=A(P_T,\eta,\lambda)$ kinematical acceptance of J/Ψ and depends on unknown J/Ψ polarization λ (see back-up slide)
- M bin migration factor to account for resolution effects evaluated from data
- $\varepsilon^{+/-}_{trig}$ $(P^{+/-}_T,\eta^{+/-})$ charge dependent single muon trigger efficiency (from T&P)
- $\varepsilon^{+/-}_{reco}(P^{+/-}_T,\eta^{+/-})$ charge dependent single muon offline reco efficiency (from T&P)

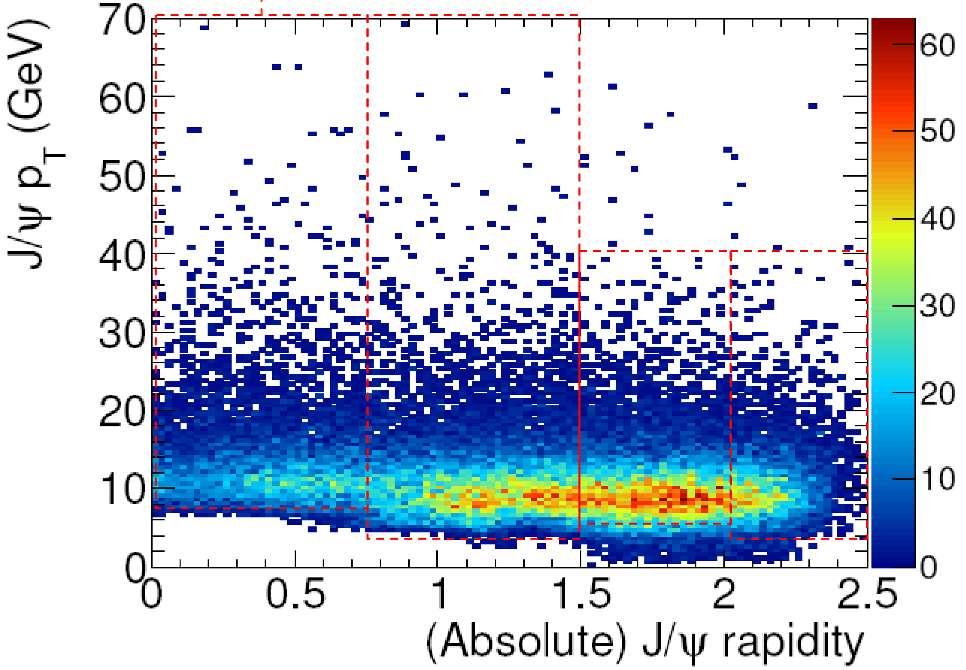
J/Ψ inclusive cross-section

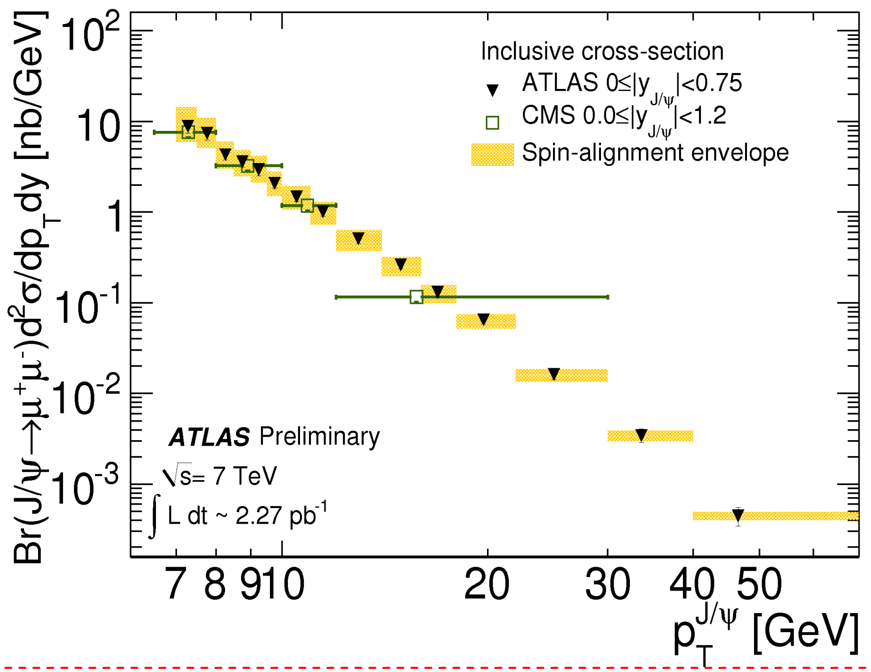
splice in pt

2.27 pb^{-1}

0<|y|<0.75

(others y bins in back-up slides)





Double differential cross-section extracted from binned likelihood fit to mass spectra in 4x15 (y,P_T) bins

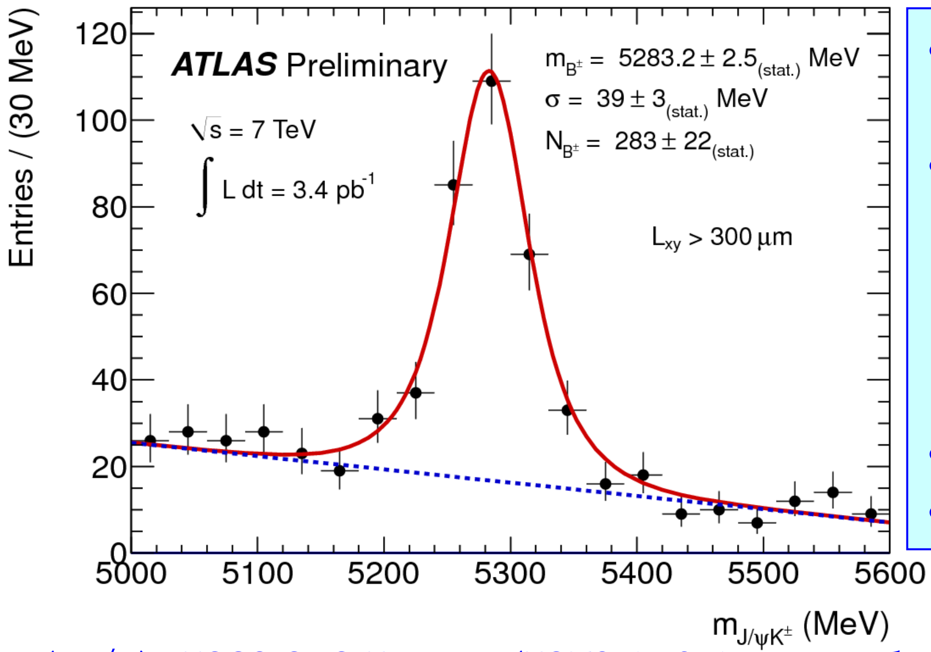
MORE ON J/Ψ ON THE TALK OF G. PASZTOR "VECTOR-MESON PRODUCTION IN ATLAS"

- Spin-alignment systematic shown by envelope on cross-section data (next polarization meas.)
- Good agreement ATLAS and CMS
- P_T up to 40-70 GeV (more high P_T stat. in 2011)

$B^{+/-} \to J/\Psi\ K^{+/-}$ observation

- Clear event topology and trigger
- Reference channel (BR rare decays such as $B_s \to \mu^+\mu^-$, ...)
- Calibration tool:
  - Inner detector calibration from Mass and Lifetime
  - b flavor tagging for CP violation studies (self flavor tagged)

Unbinned maximum-Likelihood fit with Gaussian signal and linear BG



- Muon pair in a tight J/Ψ mass window
- Muon pair refitted with J/Ψ world average mass to 3-th track with K mass hypothesis to a common vertex with chi2/dof<6
  - mass error used in signal PDF
- Overall P_T of the 3 tracks above 10 GeV
- Transverse decay length>300 μm

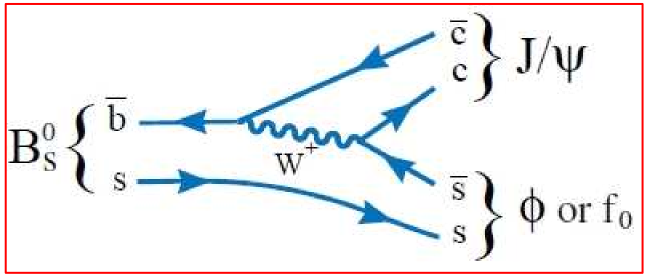
$M(B^{+/-})$=5283.2±2.5 MeV (5279.1±0.4 MeV pdg av. online)

More selection details in back-up slides

$B_s \to J/\Psi + \phi(K^- K^+)$ vs $B^0 \to J/\Psi + K^*(K^+ \pi^-)$

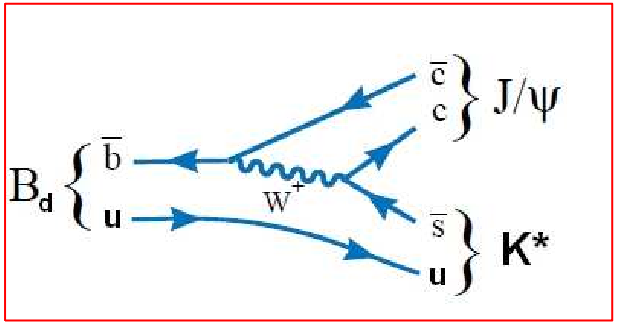
$B_s \to J/\Psi + \phi(K^- K)$ important for mixing and CP-violation:

- B_s not accessible to B-factories
- CP-violation due to mixing and expected $O(10^{-2})$. High sensitivity to New Physics.



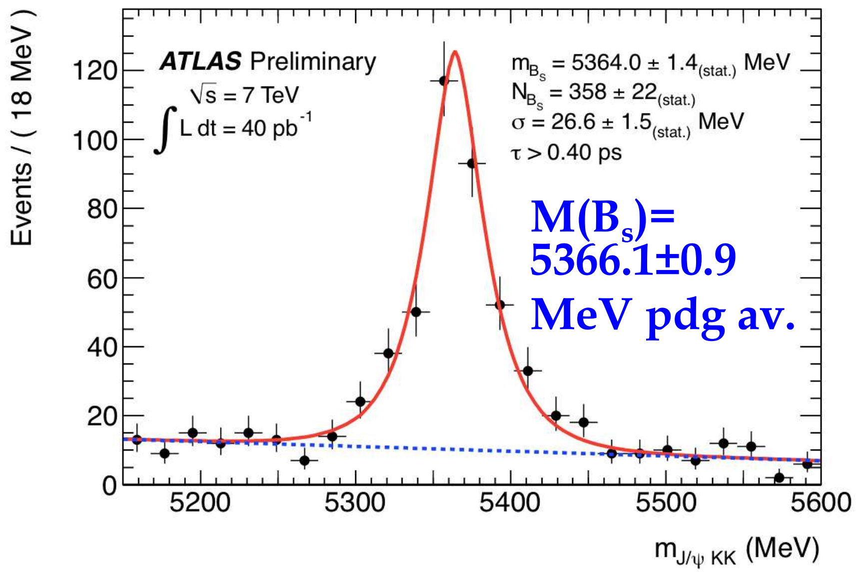
$B^0 \to J/\Psi + K^* (K^+ \pi^-)$ is testing ground for previous channel:

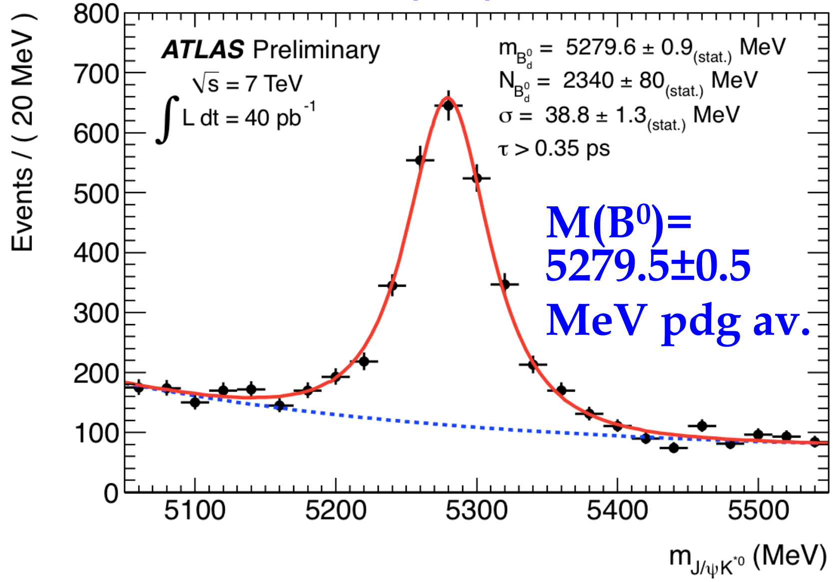
- equivalent topology and similar helicity structure
- decays differ for spectator quark
- more copious production
- self flavor tagging



$B_s \to J/\Psi + \phi$ and $B^0 \to J/\Psi K^*$ observation

Muon pair refitted with J/Ψ world average mass to 3-th and 4-th track to a common vertex with chi2/dof<2(2.5)



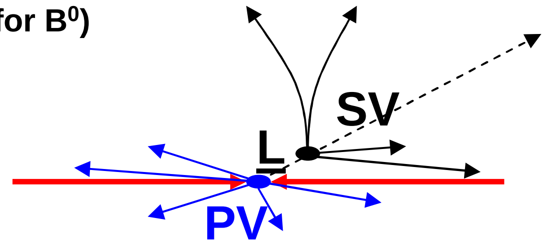


Unbinned maximum-Likelihood fit with Gaussian signal and linear BG (plus exponential for B^0)

Proper time τ cut increase significantly S/N

		m_B	σ_m	N_{sig}	N_{bkg}
B_d^0	no τ cut	5278.6 ± 1.3 MeV	36.8 ± 2.0 MeV	2680 ± 150	10280 ± 110
	with τ cut	5279.6 ± 0.9 MeV	38.8 ± 1.3 MeV	2340 ± 80	1330 ± 60
B_s^0	no τ cut	5363.6 ± 1.6 MeV	21.9 ± 1.9 MeV	413 ± 36	764 ± 17
	with τ cut	5364.0 ± 1.4 MeV	26.6 ± 1.5 MeV	358 ± 22	90 ± 7

The errors indicated are due to data statistics only.



$$\tau = \frac{L}{\beta\gamma c} = \frac{L_{xy}\, m_{B_{avg}}}{p_T(B)}$$

Open Charm hadronic decay

$$D^{*+} \rightarrow D^0\,\pi_s^+ \rightarrow (K^-\pi^+)\,\pi_s^+$$
$$D^+ \rightarrow K^-\pi^+\pi^+$$
$$D_s^+ \rightarrow \phi\,\pi^+ \rightarrow (K^-K^+)\,\pi^+$$

+ cc

- **Unbiased triggers (No muons to trigger):**
  - Minimum Bias Trigger Scintillator trigger. Located between Inner detector and endcap CALO.
  - Random triggers with minimum bias confirmed by ID tracks at level 2 trigger
- **Three tracks from weak decays with |η|<2.5 and P_T min ranging from 0.7 to 1 GeV. NO PID!!!**
- **$D^{(*)}$ meson cuts:**
  - **P_T>3.5 and |η|<2.1**
  - **$P_T/\Sigma E_T^{\mu\text{–track+calo}}$>0.02 (hard fragmentation)**
- **Fitted mass and width in agreement with MC and pdg average (online)**

$D^{*+/-} \rightarrow D^0\pi^{+/-} \rightarrow (K^{-/+}\pi^{+/-})\pi^{+/-}$

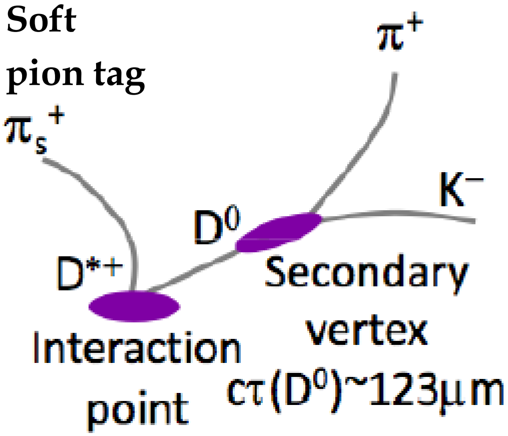
Modified Gaussian for signal

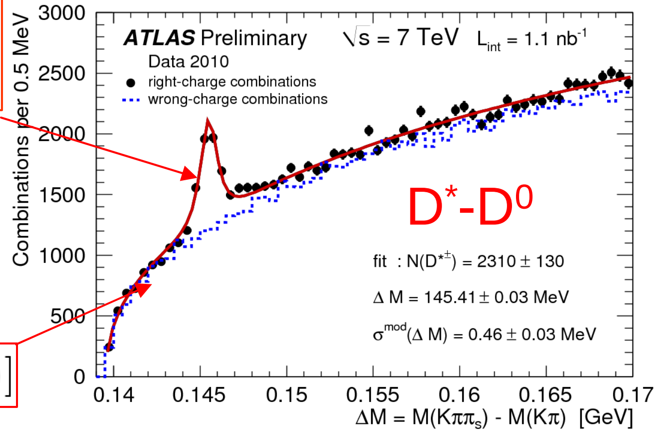
$$\mathrm{Gauss}^{\mathrm{mod}} \propto \exp[-0.5 \cdot x^{1+1/(1+0.5\cdot x)}]$$
$$\text{where } x = |(\Delta M - M_0)/\sigma|$$

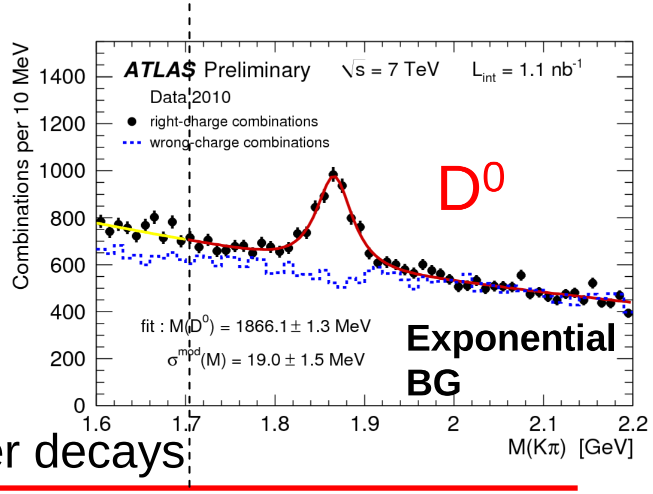
Threshold curve for BG

$$A \cdot (\Delta M - m_{\pi^+})^B \cdot \exp[C \cdot (\Delta M - m_{\pi^+})]$$

1.1 nb^{-1} Yield ~ 2k D*



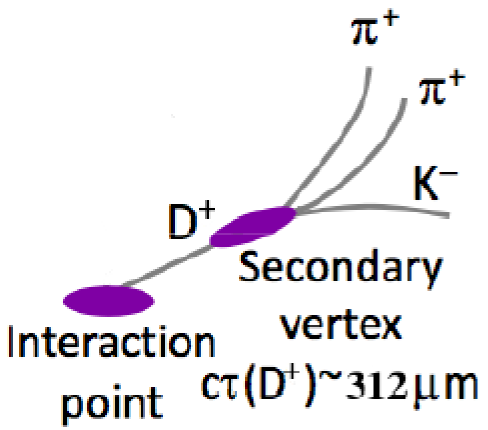




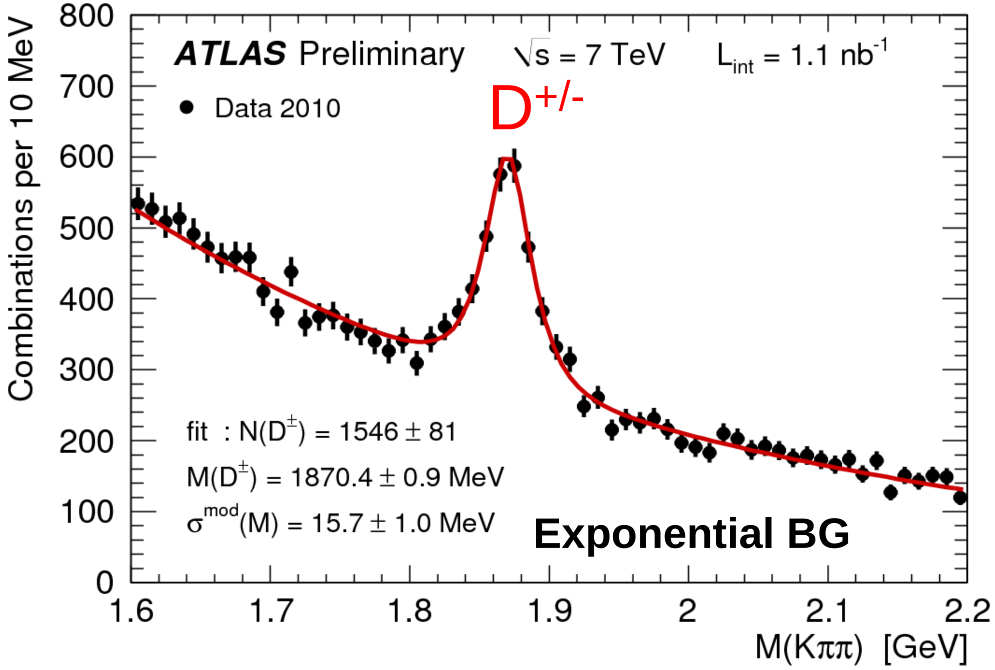
- D^0 candidates with Kπ and πK hypothesis pointing back to PV
- Soft pion pt>250 MeV and |η|<2.5
- Transverse decay length Lxy>0
- Wrong-sign $\pi_s^{\ +}K^-\pi^-$ and c.c.

M(D^*)-M(D^0) =145.41±0.03MeV (pdg av. 145.421 ± 0.01 MeV)
M(D^0)=1866.1±1.3 MeV (pdg av. 1864.91 ± 0.17 MeV)

$D^{+/-} \rightarrow K^{-/+}\pi^{+/-}\pi^{+/-}$



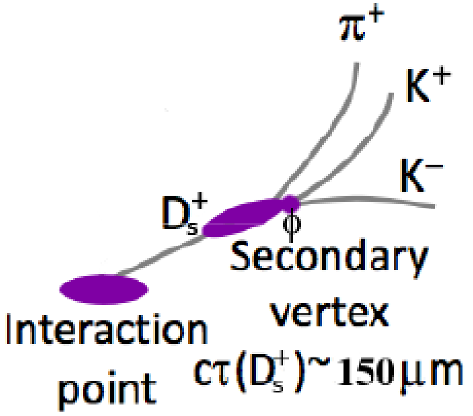
1.1 nb^{-1} Yield ~ 1.5k $D^{+/-}$



- $D^{+/-}$ pointing to PV and L_{xy}>1.3 mm
- Reject $D^{*+/-}$ with $M(K\pi\pi)-M(K\pi)<152$ MeV
- Reject $D_s \rightarrow \phi\pi$ with ϕ mass ±8 MeV and MC/Data subtraction of small remaining $D_s \rightarrow KK\pi$
- Angular cuts to suppressed combinatorial BG:
  - $\cos(\theta^*)>-0.8$: K angle in D rest frame wrt line-of-flight in lab frame

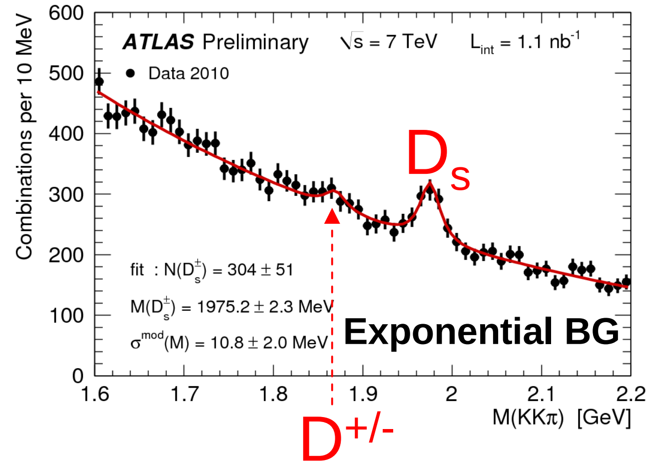
$M(D^+)$=1870.4±0.9 MeV (pdg av. 1869.5±0.4MeV)

$D_s^{+/-} \rightarrow \phi\pi^{+/-} \rightarrow (K^-K^+)\pi^{+/-}$

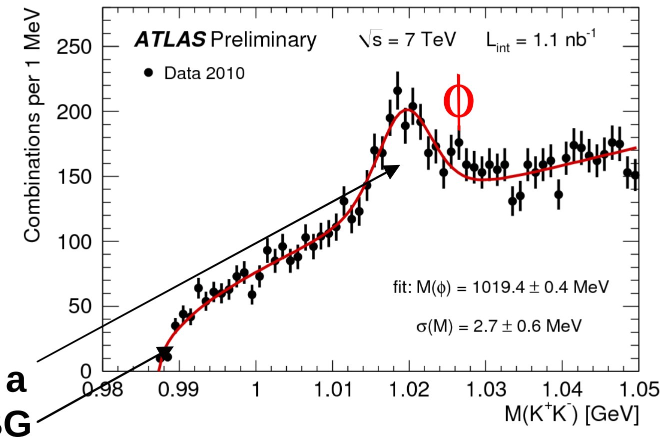


$M(D_s)$=1975.2±2.3MeV
(pdg av. 1969.0±1.4MeV)

1.1 nb^{-1} Yield ~ 300 D_s

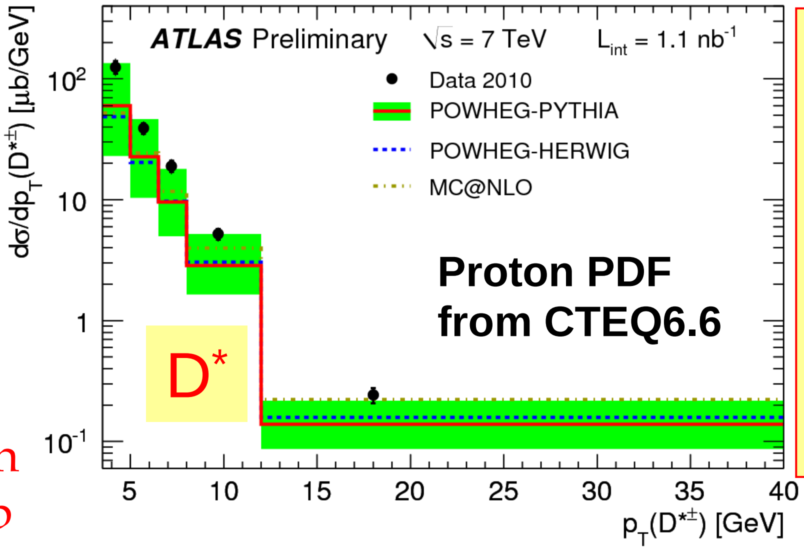


- D_s pointing to PV and L_{xy}>0.4mm
- Angular cuts to suppressed combinatorial BG:
  - $\cos(\theta^*)$<0.4: π angle in D_s rest frame wrt line-of-flight in lab frame
  - $|\cos(\theta')^3|$ >0.2 : K angle wrt π in φ frame
- No substantial contamination from $D^0 \rightarrow KK\pi$



Non Relativistic Breit Wigner convoluted with a Gaussian for Signal and Threshold curve for BG

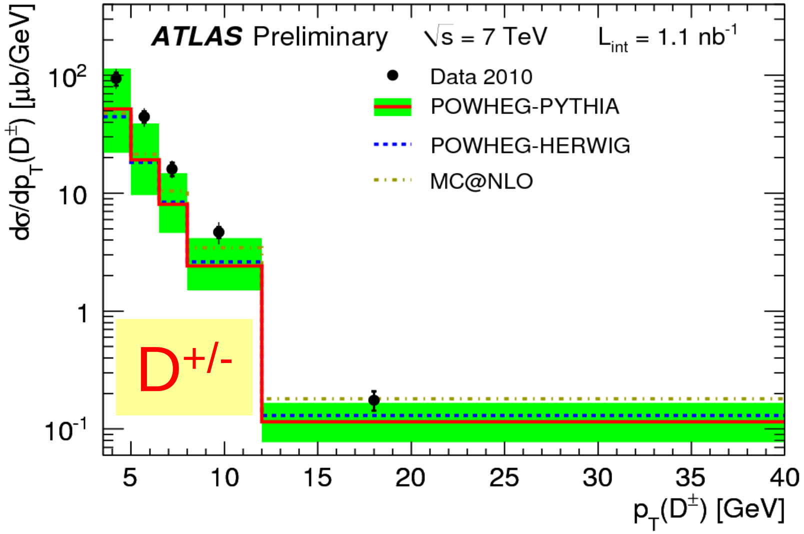
Open Charm differential xsec $d\sigma/dP_T$



- HF hadro-production from NLO calculation matched with Leading Log Parton Shower MC
- Uncertainties due to:
  - **renormalization scale**
  - **factorization scale**
  - **small: q_{mass}, PDF and hadronization**

$d\sigma/d\eta$ in back-up slides

- Experimental uncertainties dominated by: luminosity, track reconstruction and selection and D selection efficiency
- Data in visible kinematic region within the large theoretical uncertainties



Conclusions

Excellent performance of trigger, tracking and vertexing

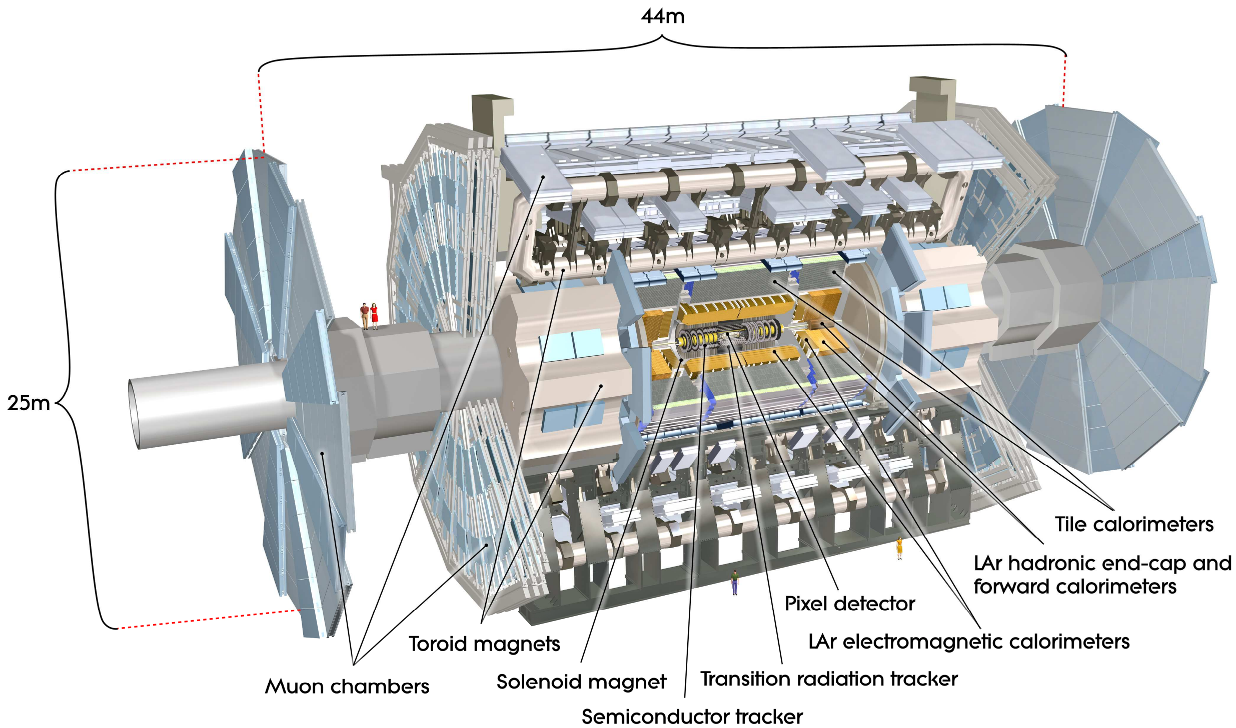
- **key features for Bphysics**

1. **New J/Ψ production results in 7 TeV pp collisions using 2.4 pb^{-1}**
   - ✓ up to very high P_T (40 GeV ~ 70GeV)
   - ✓ NEXT: polarization measurements
2. **Reconstructed 5300 B_u, 2500 B_d, and 400 B_s using 40 pb^{-1}**
   - ✓ NEXT: double life time and B_d helicity amplitude
3. **Clear $D^{*\pm}$, $D^{\pm}$ and $D_s^{\pm}$ signals reconstructed using 1.1 nb^{-1}**
   - ✓ Visible differential cross-section in agreement with the NLO predictions within the large theoretical uncertainties

Heavy Flavor program just started. Much more statistics at higher pt and analysis available soon with 2011 data.

Back-up

ATLAS detector



Three trigger levels
- L1: hardware selection of high pt object from MS and CALO (40MhZ to 75 kHz)
- L2: software confirm of L1 with all systems in Region Of Interest (2 kHz)
- L3: software with precise offline reconstruction algorithms (200 Hz)

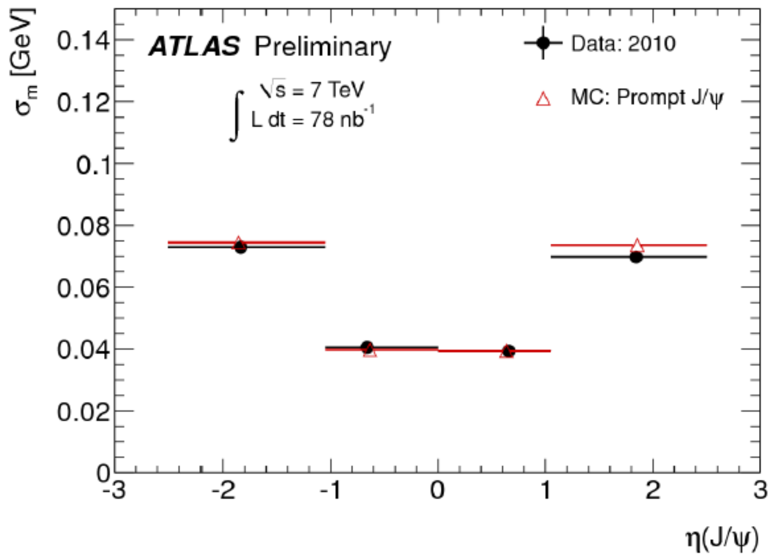
Inner detector (|η|<2.5)
- Vertexing: Pixels
- $\sigma(d_0)$~10um at high P_T
- Tracking: Strips + TRT
- 2T solenoid
- $\sigma(1/P_T)$~1.5% (low P_T)

Calorimeters (|η|<5)
- EM: accordion Pb/LAr
  $\sigma/E \sim 10\% E^{-1/2} \oplus 0.7\%$
- HCAL:Fe-Sci $\sigma/E \sim 50\% E^{-1/2} \oplus 3\%$
- FCAL:road-tube W-Cu/LAr ((3.2<|η|<5)

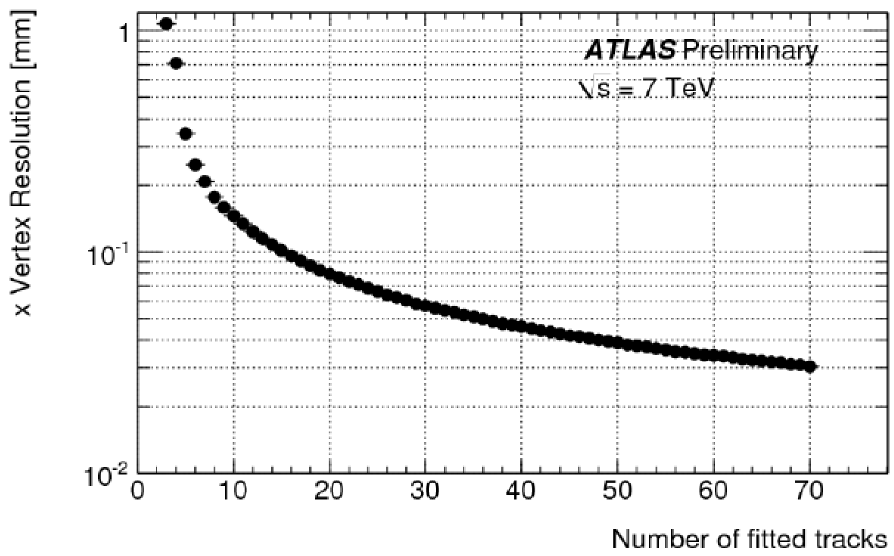
Muon System (|η|<2.7)
- Spectrometer: Monitored Drift Tube+ Cathode Strip Chamber (2<|η|<2.7)
- 4-5 Tm air core toroids σ/P_T~10% at 1TeV
- Trigger: Resistive Plate Chambert + Thin Gap Chamber σ_t~1ns

Inner detector perfomance

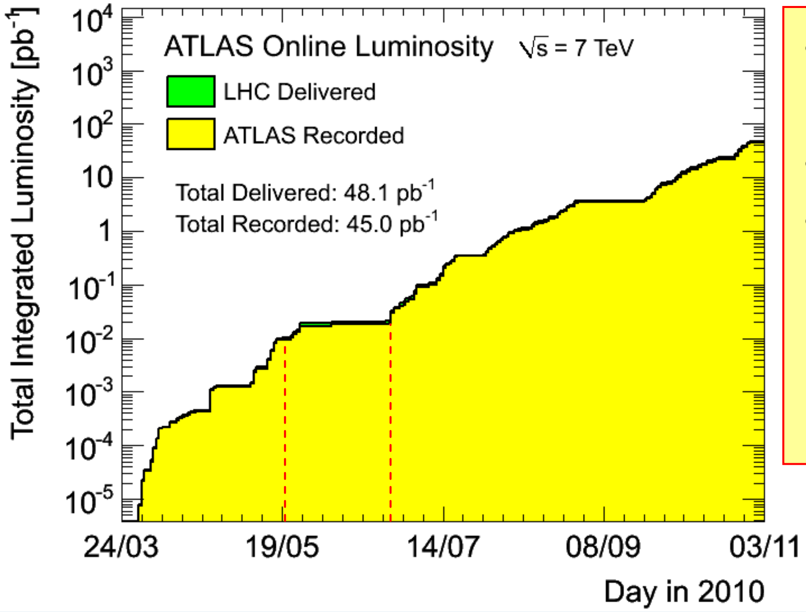
J/Y mass resolution vs η



PV resolution vs N tracks



Data sample 2010



- Trigger setting changed according to increasing instantaneous luminosity
- Peak luminosity: $2.1\times10^{32}cm^{-2}s^{-1}$
- Measured luminosity uncertainty ~ 3.4%:
  - relative value run-by-run from dedicate monitor LUCID
  - absolute value from beam current and IP size from "van der Meer" scans

Inner Tracking Detectors			Calorimeters				Muon Detectors			
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC
99.1	99.9	100	90.7	96.6	97.8	100	99.9	99.8	96.2	99.8

Luminosity weighted relative detector uptime and good quality data delivery during 2010 stable beams in pp collisions at √s=7 TeV between March 30th and October 31st (in %). The inefficiencies in the LAr calorimeter will partially be recovered in the future.

Data quality

- Uptime and data quality during stable beam extremely good for all sub-detectors.
- All sub-detectors reached the design performance

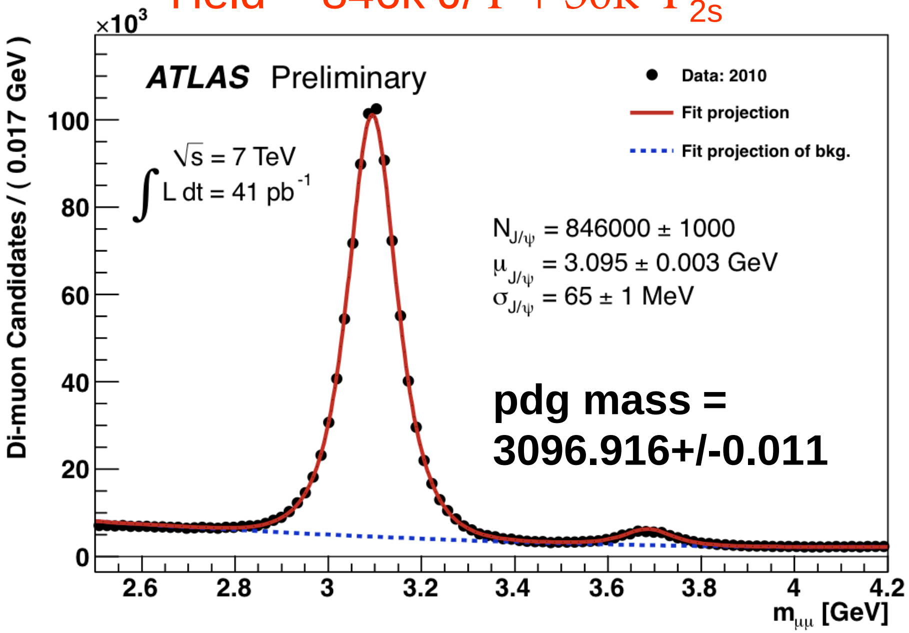
Quarkonia observation

$J/\Psi, \Psi_{2s}\ Y_{ns} \rightarrow \mu^+\mu^-$

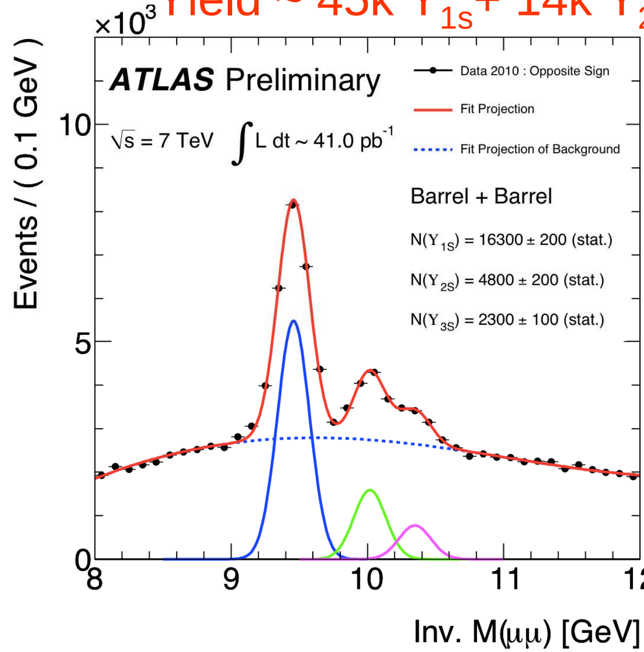
Trigger : single muon + several di-muon triggers
Selection: opposite charge μ pair (P_T>4GeV,2.5GeV) with at least 1 combined track
Fit : Gaussian signal line shape and 3-th order (4-th order) polynomial BG

FULL DATA SET

Yield ~ 846k J/Ψ + 30k Ψ_{2s}



Yield ~ 45k Y_{1s}+ 14k Y_{2s} + 6k Y_{3s}

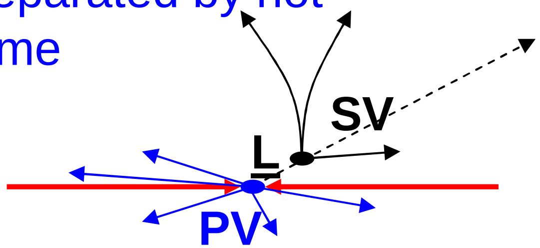


Shown Barrel-Barrel μ pair only

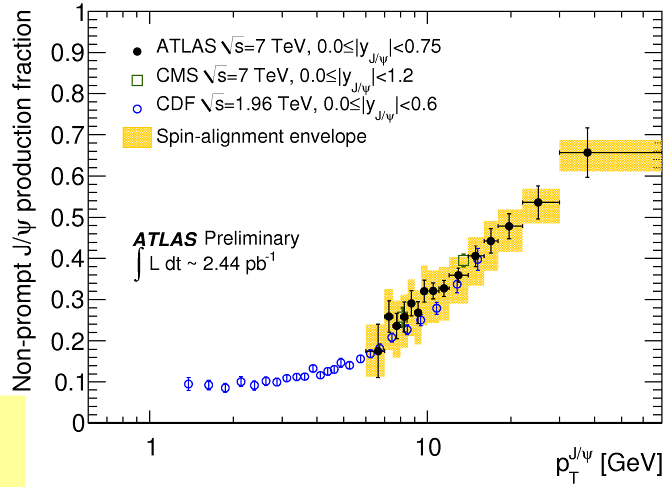
J/Ψ non-prompt fraction

J/Ψ from B decays separated by not null pseudo-proper time

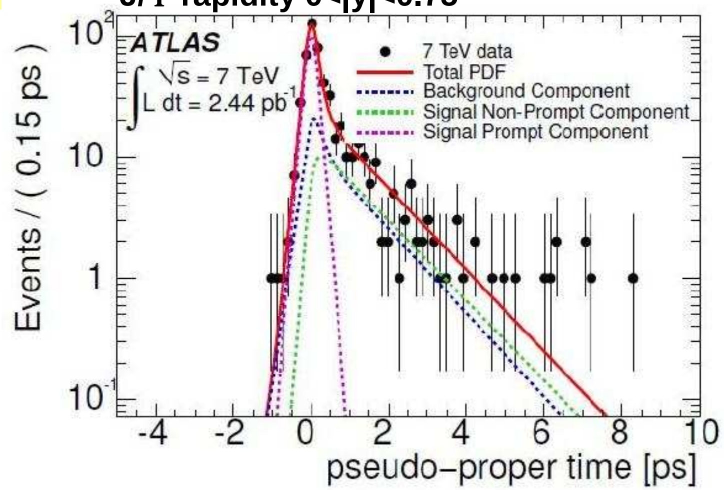
$$\tau = \frac{L_{xy}\, m_{\mathrm{PDG}}(J/\psi)}{p_T(J/\psi)}$$



τ from Lxy=L P$_T$/ P$_T$ with J/Ψ P$_T$ (B not reconstructed)



Maximum likelihood unbinned SIMULTANEOUS FIT to $m_{\mu\mu}$ and τ in (P_T,y) bin to extract the non-prompt fraction



Mass PDF:

•F_{Sig}: $F_{sig}(m_{\mu\mu},\delta_m) \equiv \frac{1}{\sqrt{2\pi}\, S\,\delta_m} e^{\frac{-(m_{\mu\mu}-m_{J/\psi})^2}{2(S\,\delta_m)^2}}$

δ_m **mass error from vertex fit and S scale factor to tune vertex fit and global**

•F_{BG}: =2-nd order polynomial

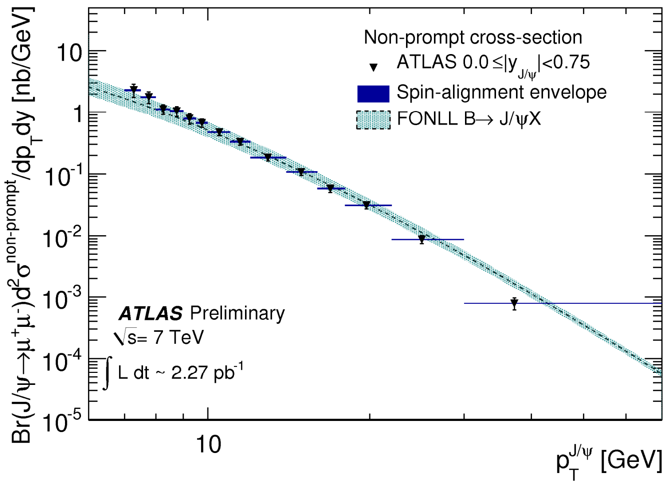
Pseudo-proper time PDF:

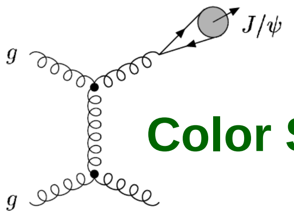
• **P_{Sig}: Exp(non-promt) + Delta (prompt) conv. with Gauss**

• **P_{BG}: Double Exp + Delta conv. with Gauss**

J/Ψ non-prompt and prompt cross-section

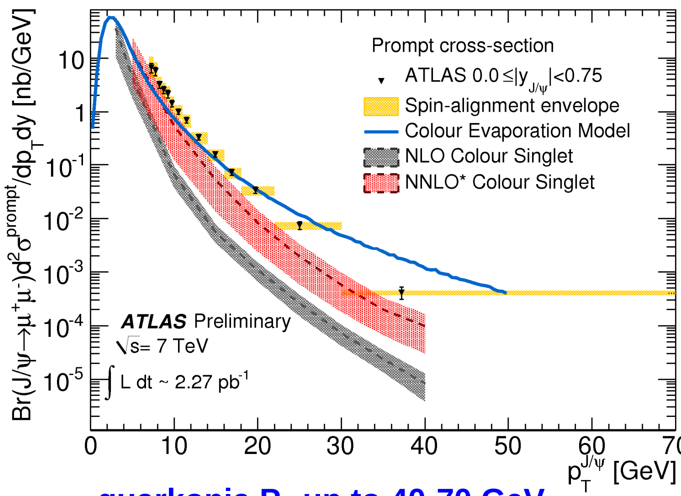
- Non-prompt cross-section in agreement with Fixed Order Next Leading Log calculation from B→J/Y+X within errors.
- Prompt cross-section in marginal agreement with partial Next-to-Next Leading Order calculation Color Singlet and Color Evaporation Model within errors.
  - ➢ Crucial to measure quarkonia polarization





Color Singlet Model

0<|y (J/Ψ)|<0.75 others in back-up slides



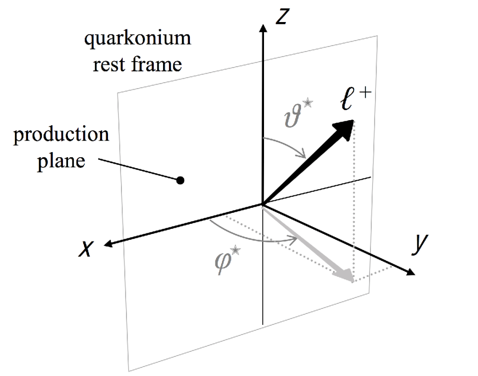
quarkonia P_T up to 40-70 GeV

Color Evaporation Model:

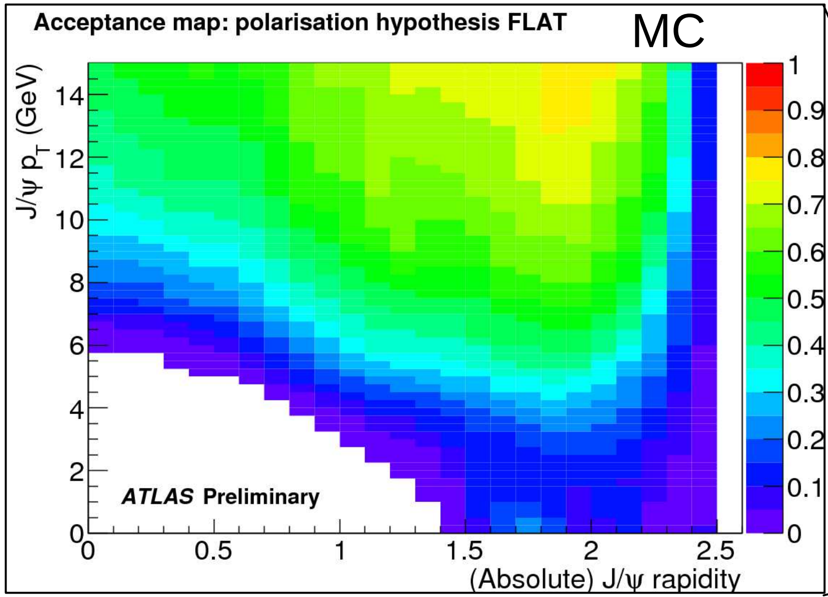
qq cross-section fraction under open flavor threshold.
Include feed-down from higher states.

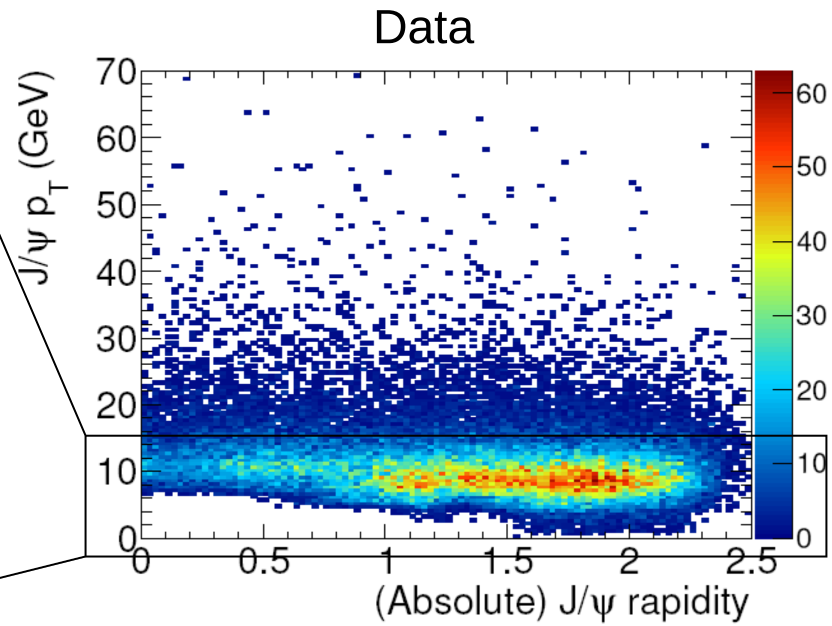
Acceptance vs J/Ψ polarization

$$\frac{d^2N}{d\cos\theta^\star d\phi^\star} \propto 1 + \lambda_\theta \cos^2\theta^\star + \lambda_\phi \sin^2\theta^\star \cos 2\phi^\star + \lambda_{\theta\phi} \sin 2\theta^\star \cos\phi^\star$$

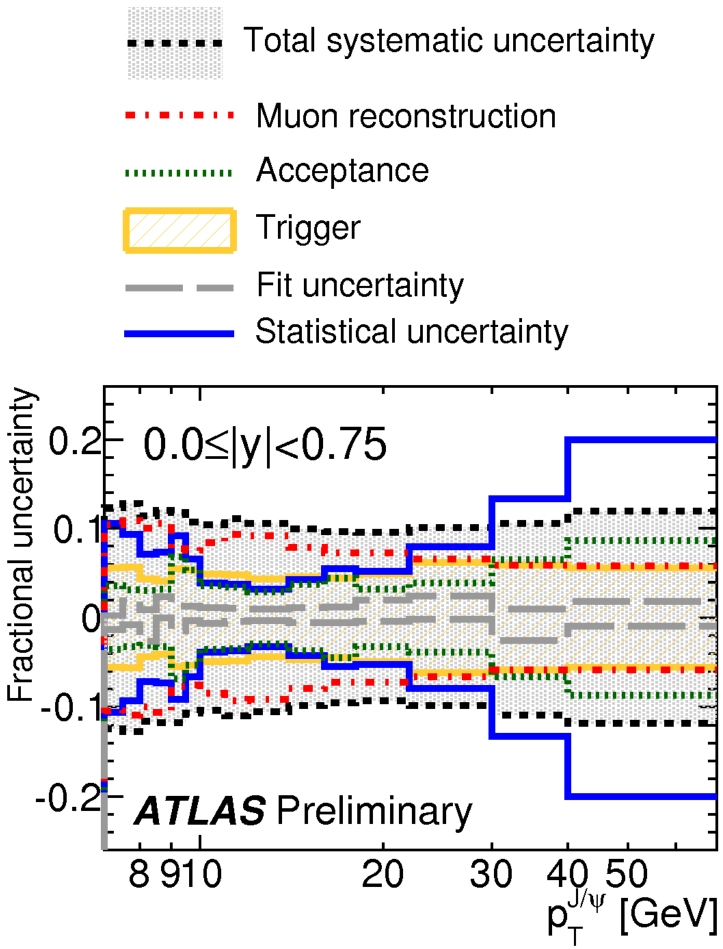


Acceptance variation evaluated with 5 most extreme cases (see back-up slide). FLAT polarization state : λ_θ=0 λ_ϕ=0 $\lambda_{\theta\phi}$=0 taken as central. Polarization, if any, expected at high P_T.





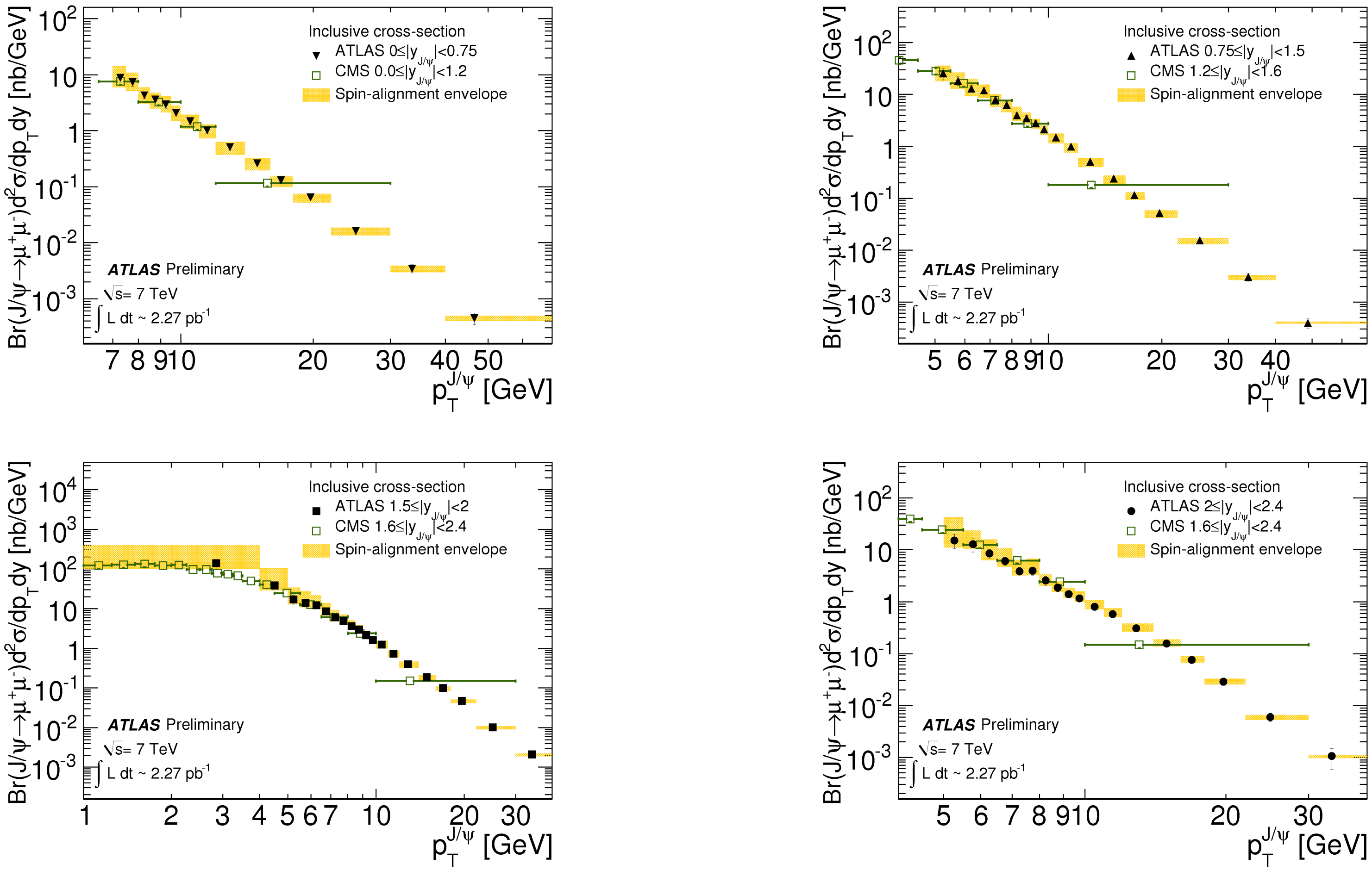
Source of systematics



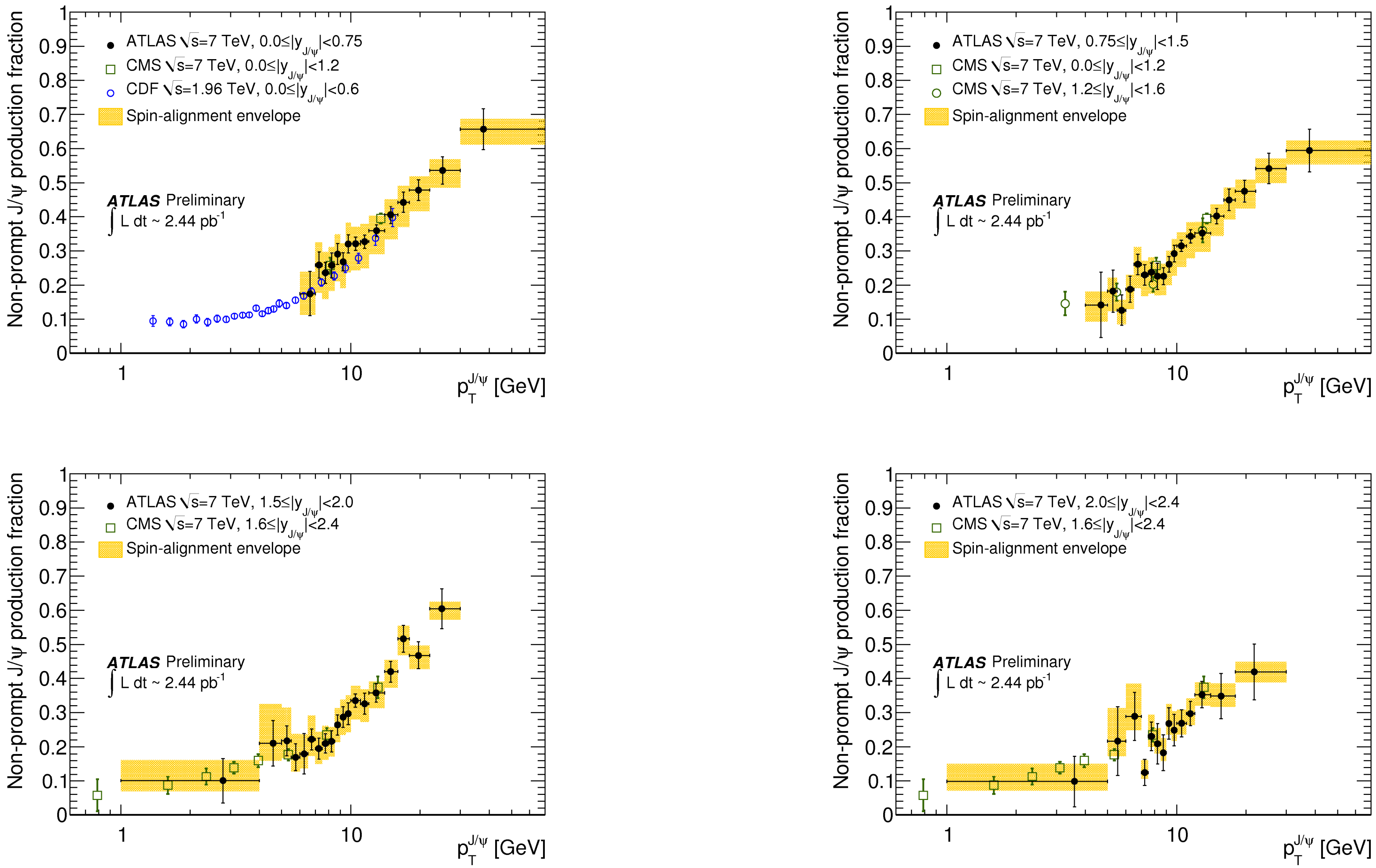
- Acceptance
- Bin migration due to resolution effect
- Muon reco efficiecy
- Trigger efficiency
- Vertex efficiency
- Luminosity

Spin-alignment evaluated by envelope on cross-section data

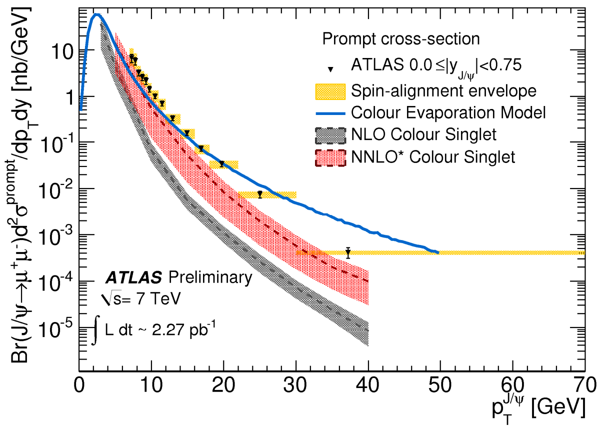
J/Ψ inclusive cross-section

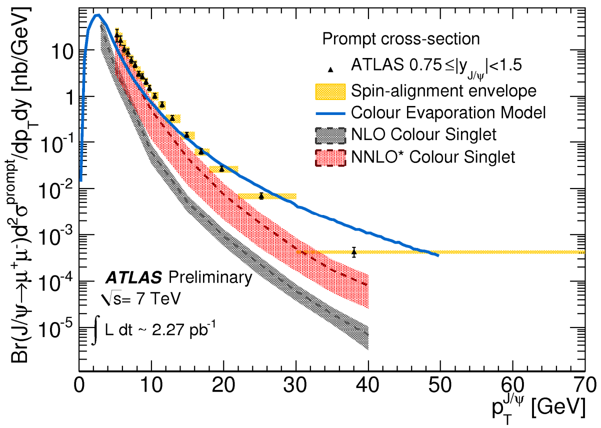


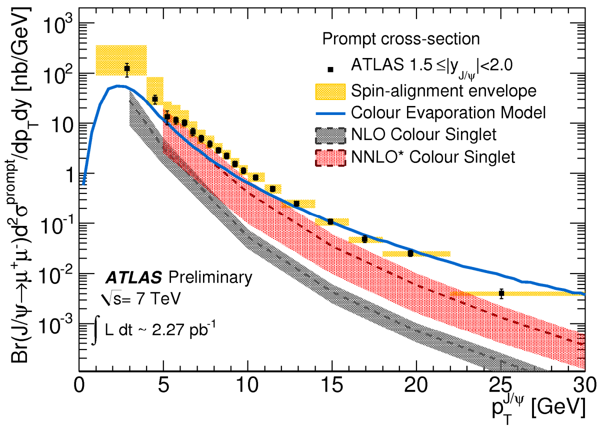
J/Ψ non-prompt fraction

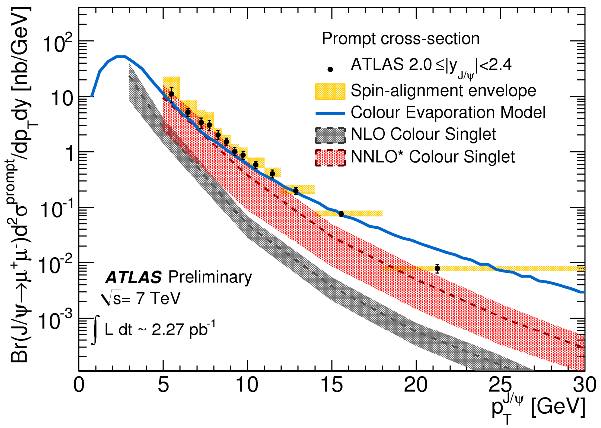


J/Ψ prompt cross-section





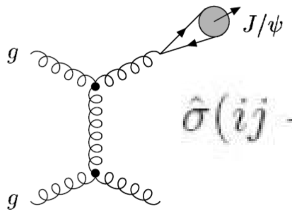




Production Models

Color Evaporation Model: qq xsec fraction under open flavor threshold (unpolarized)

Color Singlet Model

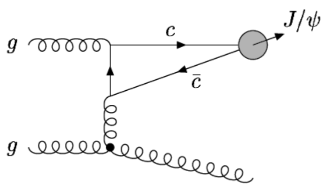


Singlet spin 1

$$\hat{\sigma}(ij \rightarrow c\bar{c}[^3S_1^{[1]}] + x)|\Psi(0)|^2$$

Meson WF at origin

NRQCD (comparison not shown here, polarized at high pt)



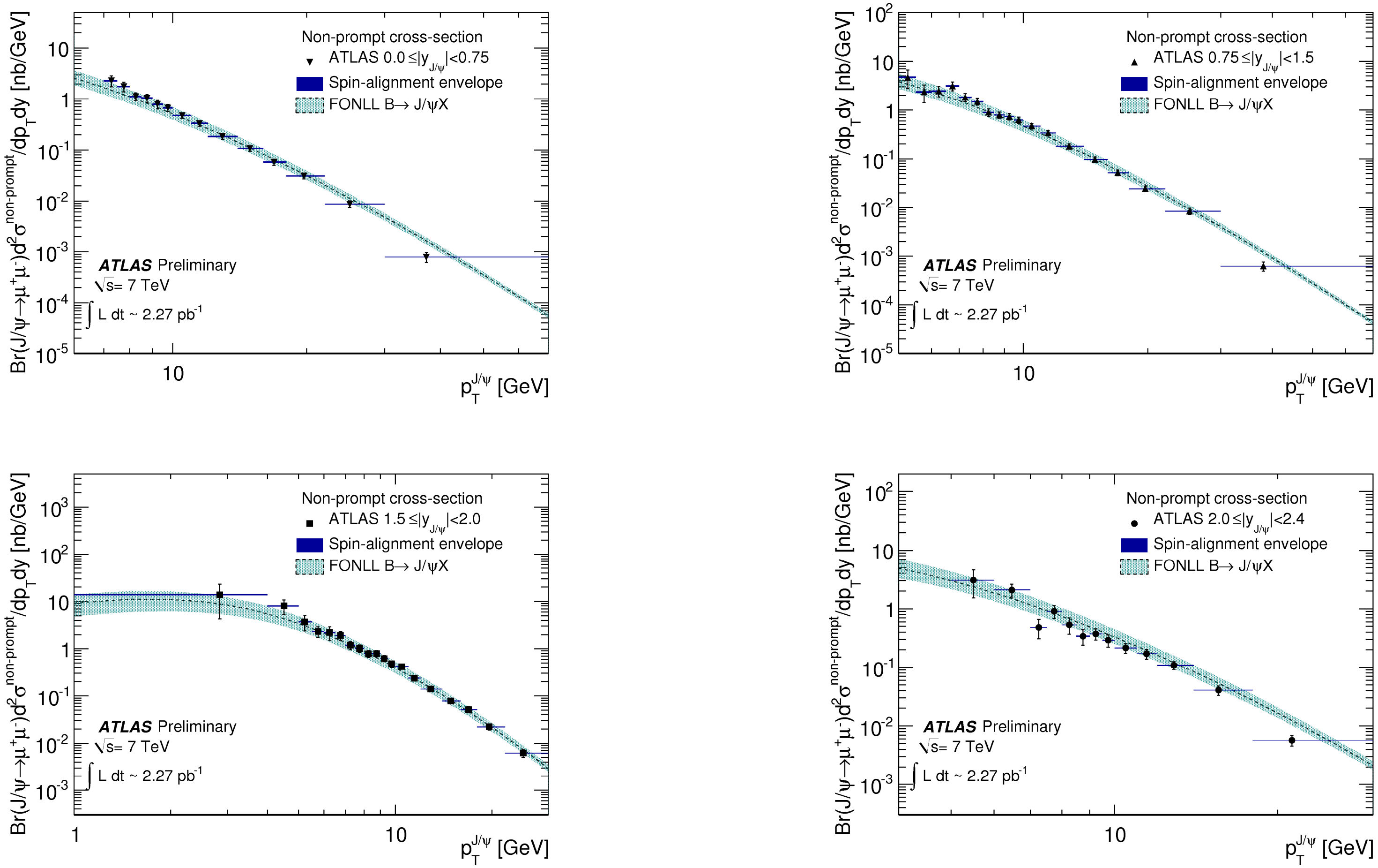
Only one diagram shown

M^H = NP matrix (soft gluons emission for colorless final meson) from data

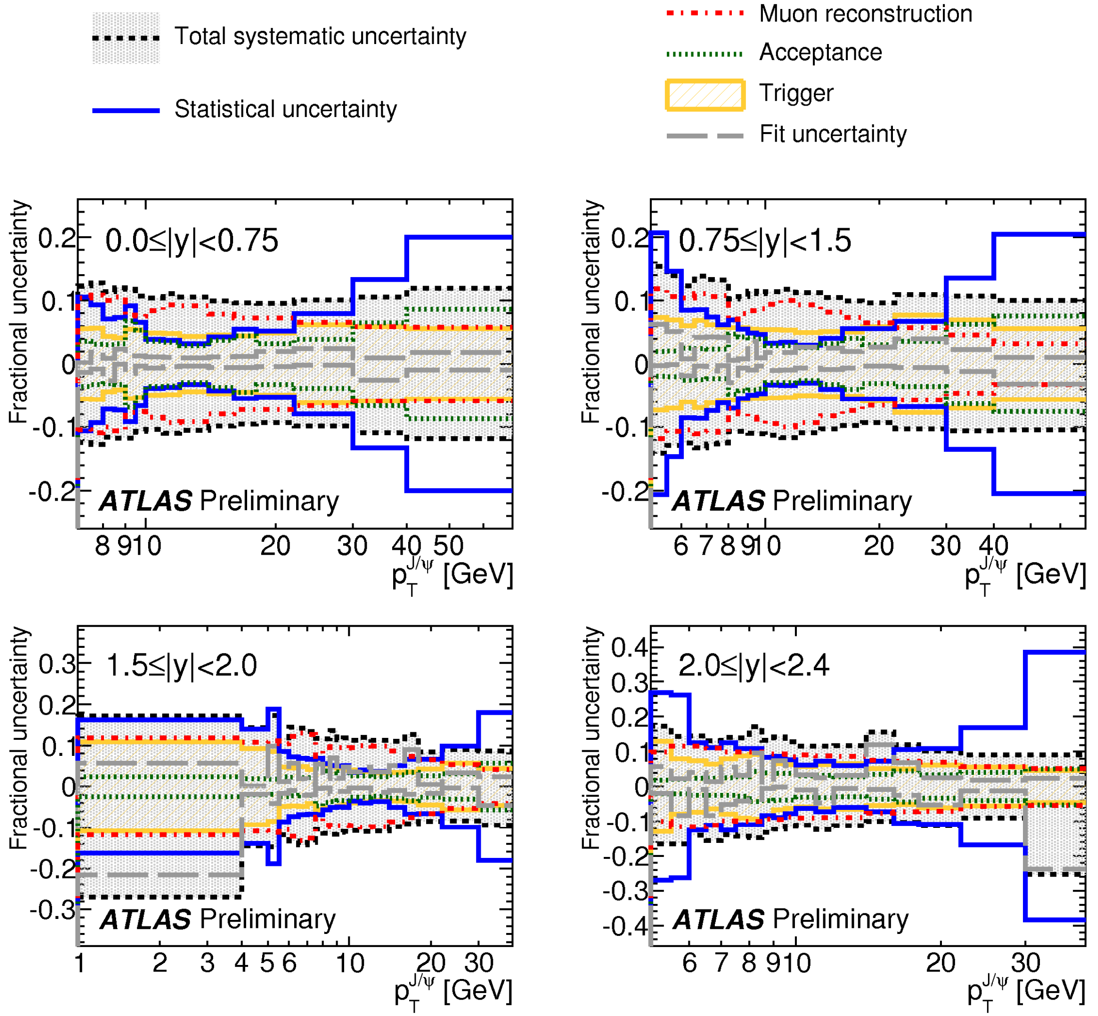
$$\sum_n \hat{\sigma}(ij \rightarrow c\bar{c}[n] + x)\langle \mathcal{M}^H[n]\rangle$$

n=color,spin,L (Octet included)

B→J/Ψ+X cross-section



J/Ψ cross-section systematic



$B^{+/-} \rightarrow J/\Psi\ K^{+/-}$ selection

- Triggers:
  - Single and di-muon L1 triggers when High Level Trigger not active.
  - Single muon High Level Trigger (pre-scaled at higher L)
  - Di-muon High Level Trigger (thresholds ranging from 4 to 10 GeV)
- Collisions:
  - one primary vertex with at least 3 inner detector tracks
- J/Ψ candidate: muon pair
  - common vertex with chi2/dof<10
  - pt1>4 GeV and pt2>2.5GeV
  - refitted mass +/-3σ from fitted mean
- B candidate: 3-rd inner detector track
  - Pt>2.5 GeV
  - muon pair refitted with J/Y world average mass to 3-th track with K mass hypothesis to a common vertex with chi2/dof<6
  - overall pt of the three tracks above 10 GeV
- Vertex displacement Lxy> 300 um:
  - Reject events where muon pair from different PV
  - Pick-up PV with highest SPT 2 or containing muon pair or 3-rd track
  - PV refitted removing muon pair and 3-rd track

$B^0 \to J/\Psi + K^*(K^+\pi^-)$ vs $B_s \to J/\Psi + \phi(K^-K^+)$ selection

- Selection specific to $B^0 \to J/\Psi + K^*(K^+\pi^-)$ and c.c. :
  - K^* candidate from 2 opposite charge tracks different from muons and pt>0.5 GeV and $|\eta|<2.5$
  - The two tracks and the muon pair constrained to J/Ψ mass are fitted to a common vertex with chi2/dof < 2.5
  - $K^+\pi^-$ and $K^-\pi^+$ hypothesis are tested and the one nearest to the K^* mass is kept
  - K^* must have mass in the range [846,946] MeV and pt>2.5 GeV

- Selection specific to $B_s \to J/\Psi + \phi(K^-K^+)$ and c.c. :
  - ϕ candidate from 2 opposite charge tracks different from muons and pt>0.5 GeV and $|\eta|<2.5$
  - The two tracks and the muon pair constrained to J/Ψ mass are fitted to a common vertex with chi2/dof < 2
  - ϕ must have mass in the range [1009,1031] MeV and each track pt>1 GeV after fit with the K mass hypothesis

- If there are more than one candidates the one with the lowest chi2/dof is chosen

Open charm differential cross-section